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THE M31 GLOBULAR CLUSTER SYSTEM: A VIEW FROM THE INFRARED

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ABSTRACT

Infrared photometry obtained with an array detector is presented for 23 globular clusters in M31, 16 of which have projected galactocentric radii of less than 1.1 kpc. A comparison with the metallicity determined for these objects by Huchra *et al.* [ApJ, 370, 495 (1991)] using optical spectra indicates that the errors in [Fe/H] determined optically have been underestimated. Combining our sample with previously published infrared photometry of M31 globular clusters produces a total sample of 84 objects. A comparison of the properties of the M31 globular cluster system as viewed in the infrared with that of the Milky Way globular cluster system indicates that the two are very similar. The mean metallicity of the nuclear globular clusters in the two galaxies is the same to within 0.11 dex (29%), as is the mean metallicity of the globular clusters outside the nucleus in the two galaxies, which is within the uncertainties of the two ⟨[Fe/H]⟩ determinations. Aside from a general enhancement in metallicity in the nuclear sample in M31, there is no evidence among the outer globular clusters for a spatial gradient of metallicity in the M31 globular cluster sample. This, too, is in agreement with expectations based on what is observed in the Milky Way globular cluster system.

1. INTRODUCTION

The globular cluster system of M31 presents a tempting target at all wavelengths. It is populous, with more than 341 probable members (Battistini *et al.* 1993), and the clusters are bright enough that detailed study is possible. Although the M31 clusters are partially resolved (Cohen & Freeman 1991), and color–magnitude diagrams of a few of them have been obtained with great effort and with the superb seeing of Mauna Kea by Christian & Heasley (1991), in general most of the light will be enclosed by an aperture not exceeding 10 arcsec in diameter.

The definitive optical study is that of Huchra *et al.* (1991) (hereafter referred to as HBK), where abundances and radial velocities for a sample of 150 clusters in M31 are given. The calibration of the abundances is discussed in Brodie & Huchra (1990), and the kinematic results are further discussed in Kent *et al.* (1989).

In the infrared, the pioneering study was that of Frogel *et al.* (1980) (henceforth FPC), who used broadband colors to study the metallicity distribution of 40 of the M31 clusters. They had access to Searle's (1980) estimates of the individual reddening for each cluster studied. This work was extended by Sitko (1984), who observed 18 clusters, 5 in common with FPC. Bonoli *et al.* (1987) observed 18 globular clusters in the halo of M31, 9 in common with FPC and 4 in common with Sitko. All of these observations were carried out with single channel detectors, and hence globular clusters near the center of M31 which appear superposed on the bright and highly spatially variable light from the nucleus and central bulge could not be observed.

To remedy this gap, in this paper we present infrared and visual observations made with array detectors of a sample of 23 clusters, 16 near the center and 7 in the outer parts of M31. The data are presented in Sec. 2, while Sec. 3 describes the abundance determinations. A comparison of the infrared view of the M31 globular cluster system with that inferred from the optical is given in Sec. 4, while Sec. 5 summarizes our results.

2. THE OBSERVATIONS

2.1 Procedures

The sample of globular clusters in M31 was selected to include those close to the nucleus from the sample of Sargent *et al.* (1977). Of the 16 nuclear globular clusters we observed, two have been observed previously in the infrared by FPC. All of these clusters have a projected distance from the center of M31 of less than 1.1 kpc, where we have adopted 3.2 pc/arcsec at the distance of M31. A second sample was chosen based on an anomaly that was noted in the tabulation of HBK abundances of globular clusters in M31 determined from optical spectra. Specifically, there is a group of very metal rich clusters in the halo of M31. We found that very suspicious, so the set of 7 clusters in the halo of M31 whose [Fe/H] as determined by HBK exceeds -0.5 dex with Kowal identification numbers less than 155 or greater than 255 (to avoid the nuclear region) were chosen as the second sample. In practice this is all clusters with [Fe/H](HBK)>-0.5 dex and with projected galactocentric radius exceeding 3.6 kpc, with the exception of K156 and K244. Note that the maximum R(proj) in this group is 14.6 kpc (for K348), the minimum is 3.6 kpc (for K130), and the median R(proj) is 6.6 kpc. The specific clusters included here are K39, K82, K90, K96, K130, K305, and K348. We refer to this group subsequently as the AMR ("apparently metal rich") sample. Two of these have been observed previously in the infrared by FPC and two by Bonoli *et al.* (1987).

All but one of the nuclear globular clusters in our sample were observed in the visual using an imaging CCD detector on the 60 in. telescope at Palomar Mountain on the night of 1992 Sept. 19. The night was photometric and the seeing was

TABLE 1. M31 globular cluster photometry.

Object	K (mag)	σ(K) (mag)	No. (K)	J (mag)	σ(J) (mag)	No. (J)	V (mag)	[Fe/H](IR)
K39	14.10	0.06	2	14.78	0.05	2	...	−1.24
K82	14.20	0.00	2	...	...	0	...	−1.59
K90	13.64	0.05	2	14.42	0.00	2	...	−0.99
K96	12.69	0.04	4	13.46	0.00	2	...	−1.12
K130	12.94	0.00	2	13.77	0.01	2	...	−0.64
K148	12.92	0.02	4	13.54	0.00	2	15.18	−1.93
K165	12.10	0.04	4	12.98	0.02	2	15.24	−0.69
K168	13.32	0.03	2	14.10	0.06	2	16.15	−1.13
K169	13.04	0.05	4	13.75	0.00	2	15.81	−1.35
K174	12.84	0.04	4	13.84	0.04	2	16.37	−0.13
K175	14.28	0.04	2	15.06	0.00	2	17.08	−1.16
K177	12.50	0.05	4	13.42	0.00	2	15.99	−0.32
K184	14.30	0.07	2	15.18	0.04	2	17.12	−0.91
K185	11.66	0.01	2	12.43	0.01	2	14.45	−1.19
K189	12.62	0.05	2	13.37	0.03	2	15.44	−1.22
K190	14.11	0.07	2	14.62	0.09	2	16.62	−1.96
K194	14.45	0.03	2	15.31	0.05	2	17.07	−1.11
K198	12.80	0.08	4	13.71	0.05	2	...	−0.60
K200	13.31	0.02	2	13.95	0.02	2	15.85	−1.66
K207	13.24	0.07	2	14.12	0.01	2	16.24	−0.78
K208	13.69	0.01	2	14.60	0.02	2	16.82	−0.61
K305	12.67	0.00	2	13.48	0.02	2	...	−1.00
K348	13.58	0.02	2	14.20	0.01	2	...	−1.57

1.2 arcsec. The 6 frames of standard stars show a rms deviation of 0.04 mag about the mean photometric zero point. Integrations were 400 s long through a *V* filter, with 0.24 arcsec/pixel, using a 800×800 pixel Texas Instruments CCD detector. Aperture photometry using a 14 pixel radius (corresponding to an aperture diameter of 6.7 arcsec) was derived using standard Figaro routines. The highly variable galaxy background was treated as "sky" and removed. There are at least 2 observations of most clusters.

The *V* magnitudes for 15 nuclear globular clusters in M31 are 0.08 mag fainter in the mean than those of Battistini *et al.* (1987) measured by digitizing a single Schmidt plate. The rms dispersion about the mean is 0.10 mag. We use the Palomar measurements when available, and those of Battistini *et al.* (1987) for the remaining clusters.

Infrared observations were made at the 200 in. Hale telescope on Palomar Mountain on the nights of 1993 August 5 and August 6. The nights were photometric and the seeing was about 1 arcsec. Ten standards were observed from the list of Elias *et al.* (1982) during the first night and eleven the second night to define the photometric zero points. The rms deviation about the mean was 0.03 mag at *J* and 0.04 at *K*. A measurement at *J* or at *K* consisted of co-adding three integrations of 30 s each, then moving the telescope 5 arcsec East where a second set of 3 co-added integrations were made. There are thus two independent measurements of each object in each color. All exposures were guided.

The array used was a 58×62 pixel InSb array from Hughes SBRC. The scale is 0.31 arcsec/pixel. An aperture 9 pixels in radius, corresponding to 5.6 arcsec in diameter, was used. Ideally a larger diameter aperture would be used, but given the array size, and the need to measure the background accurately, this choice seemed reasonable. Its a good match to the optical photometry (aperture diameter of 6.7 arcsec). Note that with the use of an array, centering errors due to the need to "peak up" on a source with single channel detectors are very much smaller.

After removing the dark frame and linearizing the data, Figaro scripts were used to correct for bad pixels and flatten the data. Standard techniques were used for the aperture photometry. An independent measurement was made for each of the two positions at which the cluster was imaged.

Three M31 globular clusters, K90, K305, and K348, were re-observed at *J* and *K* with the 200 in. telescope on 1993 Dec. 29. The night was photometric and the seeing was 2.0 arcsec at the zenith. Two standards from Elias *et al.* (1982) were observed immediately after these measurements. The observations were obtained with a half functional Nicmos 3 256×256 infrared array with a scale of 0.17 arcsec/pixel and field size of 21×42 arcsec. The measurements were made in photometric conditions at airmass 1.75, and an aperture of 22 pixels radius, corresponding to 7.3 arcsec in diameter, was used here. The mean difference between the December and the August measurements was 0.08 mag in both *J* and *K*, with $\sigma[\Delta(J)]=0.09$ and $\sigma[\Delta(K)]=0.03$ mag. The December measurements were used only to confirm the August photometry. Their values were not averaged in nor included in Table 1.

The visual and infrared measurements for globular clusters in M31 are listed in Table 1. For each of the infrared colors, the mean magnitude and the number of independent measurements is given, as is the rms deviation about the mean. In most cases the σ is gratifyingly small.

2.2 *Comparison With Published Photometry*

There are 4 clusters in common with FPC. For 3 of them, the agreement is good. For K90, it appears that a different

TABLE 2. Comparison of [Fe/H](IR) with [Fe/H](Spec.).

	Nuclear sample		AMR sample	
Method	[Fe/H] (dex)	No. of clusters	[Fe/H] (dex)	No. of clusters
IR	−1.04 (±0.13)	16	−1.16 (±0.13)	7
IR (using BH fits)	−1.00 (±0.15)	16	−1.15 (±0.15)	7
HBK	−0.74 (±0.18)	12	−0.31 (±0.11)	7
IR−HBK	−0.22 (±0.22)	12	−0.86 (±0.17)	7
(IR−HBK)/σ(HBK)	−0.62	12	−1.95	7
(IR using BH fits−HBK)/σ(HBK)	−0.54	12	−1.89	7

object was observed by FPC than by us, as there is a 0.5 mag disagreement at K. There are 2 clusters in common with Bonoli *et al.* (1987), K305 and K348. There the agreement is unsatisfactory in both cases. As mentioned above, these 3 discrepant clusters (K90, K305, and K348) were re-observed in December with a different infrared array. There is good agreement between the August and December measurements, and both are inconsistent with the previously published values.

For these three discrepant clusters, we checked the coordinates stored by the telescope control system in the header of our images to make sure that the right object was observed. In all 3 cases our pointings were correct to within 5 arcsec or better, based on the coordinates of Sargent *et al.* (1977). Also we could see the clusters and the surrounding field objects in the guiding television system, so there is no chance that the objects were misidentified by us. In all 3 cases our frames indicate that there is no object of brightness comparable to the globular cluster in the field of the array. Furthermore, the infrared array frames indicate that the object measured is spatially extended and appears more or less round, i.e., it is a cluster and not a star or a galaxy. In 2 of the 3 cases, both J and K are discrepant, yet J and K were measured on different nights during the August run. The December measurements support the values measured in August. We must conclude that our measurements are correct, and that unknown problems afflict the previously published infrared photometry for these 3 M31 globular clusters.

The coordinates used by HBK come from Kent *et al.* (1989). We initially used these to try to find the M31 globular clusters. But with such a small infrared array, accurate coordinates are vital, and it quickly became apparent from experience at the telescope that these coordinates were unsatisfactory. We note that the Sargent *et al.* (1977) coordinates agree well with those of Battistini *et al.* (1987), but the Kent *et al.* (1989) coordinates for K96, K148, K198, and K200 disagree with the two previously cited references by 20 to 50 arcsec. We believe that the Sargent *et al.* (1977) and Battistini *et al.* (1987) values are correct. Brodie (1994) advises that this is the result of a "rounding/truncation error which occurred when the table" in Kent *et al.* (1989) "was generated."

3. ABUNDANCES FROM INFRARED COLORS

As is well known, infrared colors of old composite stellar systems can be used to determine abundances. This was first pointed out by Aaronson *et al.* (1978) (hereafter referred to as ACMM), who analyzed the galactic globular cluster system in this way. FPC used identical techniques to examine the properties of the M31 globular cluster system. We have taken the latest metallicities for the low reddening calibrating clusters of ACMM from the work of Zinn & West (1984), as updated in Armandroff & Zinn (1988). The best linear relationships we obtain for the de-reddened colors are

$$[\mathrm{Fe/H}] = -4.886(\pm 0.434) + 1.487(\pm 0.192)(V-K)_0,$$

$$[\mathrm{Fe/H}] = -4.437(\pm 0.385) + 4.454(\pm 0.591)(J-K)_0$$

with correlation coefficients of 0.89 and 0.86, respectively. These are somewhat different from those adopted by Brodie & Huchra (1990). The difference in [Fe/H] predicted from $(V-K)_0$ over the relevant range is insignificant, always less than 0.06 dex, but our abundance from $(J-K)_0$ is 0.2 dex lower than that of Brodie and Huchra at the reddest values reached by the M31 globular clusters.

A major complication is that we have no reddening values for the M31 globular clusters we observed. We have therefore adopted the standard foreground reddening to M31, $E(V-K)=0.28$ mag, $E(J-K)=0.05$ mag for all clusters which do not have specific values of reddening assigned in FPC, equivalent to ignoring any absorption internal to M31. In practice, this is probably acceptable for the outer sample of 7 clusters, but for the nuclear sample, we must regard the abundances derived from measured infrared colors as upper limits to the true abundances.

The infrared abundances, derived by averaging the results from $(V-K)_0$ and from $(J-K)_0$, are given in the last column of Table 1. We compare these [Fe/H](IR) with those obtained from optical spectroscopy by HBK. Note that the results inferred from $(V-K)$ colors and from $(J-K)$ colors for the nuclear sample agree to within 0.10 dex. But since the reddening vector and the abundance vector are parallel to within 8° in the $(J-K)$ vs $(V-K)$ plane, this is not surprising, and we cannot use this result to infer anything about the magnitude of the reddening. Table 2 gives comparisons of our abundances and the HBK abundances for the nuclear and AMR cluster sample. Examples are given to illustrate the small change that results from adapting the fits of abundance versus infrared color of Brodie & Huchra (1990) instead of those given above. The final 2 columns give the difference between [Fe/H] from IR photometry and from optical spectroscopy divided by the error estimate for each individual [Fe/H] determination from HBK.

TABLE 3. Mean abundance for nuclear and outer samples of globular clusters in M31.

	Nuclear			Outer	
Sample	[Fe/H] (dex)	No. of clusters	R(cut) (kpc)	[Fe/H] (dex)	No. of clusters
M31−IR	−1.04 (±0.10)	24	1.5	−1.28 (±0.07)	60
M31−HBK	−0.66 (±0.12)	23	1.5	−1.30 (±0.05)	127
Milky Way	−0.93 (±0.18)	14	1.8	−1.38 (±0.05)	119

The abundance of the sample of 7 AMR globular clusters derived by HBK is in serious conflict with the infrared derived abundance. The average difference between [Fe/H](IR) and their values is −0.86 dex, and this corresponds to almost a 2σ change in the mean abundance for this group of globular clusters in M31, where σ is not the uncertainty in the mean abundance but the much larger uncertainty in each individual [Fe/H] determinations. The reported uncertainty in HBK's mean [Fe/H] of this AMR cluster sample is less than 0.2 dex. Our abundances derived from infrared photometry put all the clusters in the AMR sample below 1/4 solar metallicity. We note that in our Galaxy, most of the globular clusters with [Fe/H]>-0.5 dex lie close to the galactic center, except for NGC 5927 with R_{GC}=4.7 kpc and Pal 8, with R_{GC}=20.9 kpc.

The same discrepancy is true of the nuclear sample, but here the effect is much smaller. The average difference for the 12 nuclear clusters we observed which have optical spectroscopy in HBK, [Fe/H](IR)−[Fe/H](HBK), is −0.22 dex, corresponding to a 0.6σ shift downward in abundance.

While one may try to throw the blame for this discrepancy at the infrared derived abundances, that seems unlikely. There is no reason to expect this method, tried on galactic globular clusters many times, to fail. Optical spectra show no indications of emission lines that might distort the infrared colors or of any significant population difference with the galactic globulars (Brodie & Huchra 1990).

As described by Brodie & Huchra (1990), the spectra used by HBK were originally obtained for an analysis of the kinematics of the M31 globular cluster system. They are not a homogenous set; two different detectors were used. They are of rather low signal-to-noise ratio, particularly for the faintest objects, and rather low spectral resolution (8 Å) to be used to estimate abundances. Perhaps their uncertainties are underestimated.

We note that Jablonka *et al.* (1992) and Bica *et al.* (1992) have obtained low dispersion spectra of 7 globular clusters in M31 which are comparable to those of HBK. For their two most metal-rich objects, K177 and K158, both of which have small projected galactocentric radii, they obtained significantly higher abundances than we have deduced here. They decided that K158 is a cluster belonging to the inner disc, hence not relevant here. For K177 they derive [Fe/H] =+0.52 dex, while we obtain −0.32 dex, and HBK deduce −0.15 dex. The details of their adopted W_λ (abundance) relationships are given in the Appendix to Jablonka *et al.* (1992).

4. THE M31 GLOBULAR CLUSTER SYSTEM

Combining the entire sample of globular clusters in M31 with infrared photometry, i.e., FPC, Sitko (1984), Bonoli *et al.* (1987), and Table 1 of this paper, we obtain a total of 84 objects. [The cluster candidate Bo37 (also known as V327), which has $(V-K)\approx 5$ (Bonoli *et al.* 1987), was omitted. It was rejected as a M31 globular cluster by Sargent *et al.* (1977) and by Battistini *et al.* (1993).)] If a cluster was observed by us, we adopted our measurements. Otherwise, in all cases where multiple measurements of a M31 globular cluster exist, we simply averaged all available J or K magnitudes. The V magnitudes are either from the observations in Table 1 above or from Battistini *et al.* (1987). Just under half of the objects have individually determined reddenings. This sample is sufficiently large and sufficiently unbiased in its spatial distribution that we can use it to attack the following issues: are globular clusters near the nucleus of M31 more metal rich than those outside it, outside the nucleus is there any trend of decreasing metallicity with increasing radius, how does the infrared abundance pattern compare with that determined from optical spectroscopy by HBK, and how do these results compare with what we see in the Milky Way globular cluster system?

We know from the work of Zinn & West (1984) that in the Milky Way, the globular clusters closest to the galactic center are in the mean more metal rich than those outside the galactic bulge. Furthermore the metallicity distribution is, as is well known, double peaked, with peaks at high and intermediately low metallicities. The relevant results for the M31 globular cluster system are given in Table 3, where R(cut) is the projected radius in kpc separating the nuclear and outer samples. Recall that in M31, we only know the projected radius of a cluster, not the true galactocentric radius.

Typical values of σ for individual measurements about the mean within each group are 0.5 dex; the errors given in Table 3 are the uncertainties in the mean [Fe/H] of each group.

Although our selected sample of 7 AMR clusters had big discrepancies in [FeH](IR)−[Fe/H](HBK), the majority of the outer clusters in M31 do not. The agreement between the mean abundance for the outer clusters in M31 deduced from the sample with IR photometry and that from optical spectra given by HBK is very good, and is negligably (≤0.10 dex) higher than that of the Milky Way. Furthermore, it is apparent that with the lower nuclear abundances found using [Fe/H](IR), which themselves are, in many cases, upper limits, the M31 globular cluster system very closely resembles the

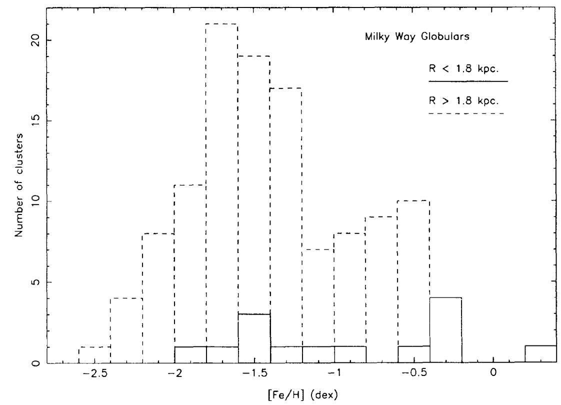

FIG. 1. A histogram of abundance is shown for the Milky Way globular cluster system. The dashed lines denote clusters with galactocentric radius more than 1.8 kpc, while the solid lines denote clusters with galactocentric radius<1.8 kpc.

Milky Way system in its mean abundance at all galactocentric radii.

Figures 1–3 give the histogram of abundance for the sample of M31 globular clusters with IR photometry, those from HBK with optical spectroscopy, and the Milky Way system. Note that the sample of M31 globular clusters with IR photometry is in fact, as a result of the present work, biased towards nuclear clusters. The fraction of that sample with R(proj)<1.5 kpc is 29%, while the same for the HBK sample is only 15%.

The last point to consider is whether there is a spatial gradient outside the nuclear area. It is well known that such an effect, if present, is very weak in the Milky Way. Figure 4 shows the relevant plot for the M31 IR sample. Outside the nucleus there is no obvious trend, which is not surprising since the projection of galactocentric radii will tend to smooth out any gradient that might be present.

5. SUMMARY

Infrared photometry has been obtained at the 200 in. Hale telescope at Palomar Mountain using an array detector for a

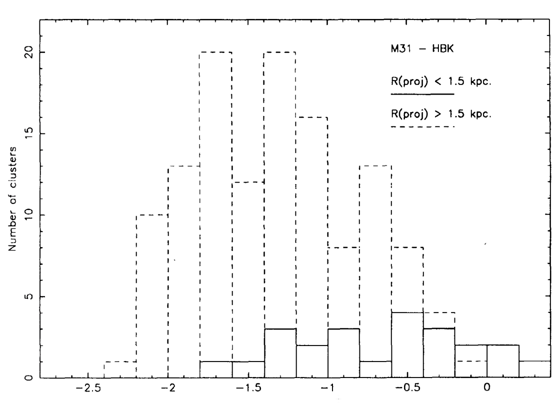

FIG. 2. The same as Fig. 1 for the M31 globular cluster system as determined from optical spectroscopy by HBK. The cut is made at a projected galactocentric radius of 1.5 kpc.

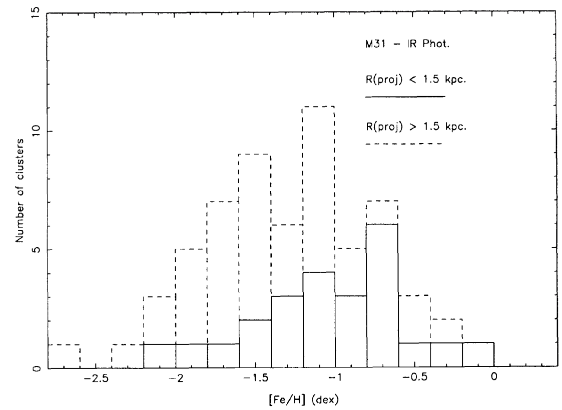

FIG. 3. The same as Fig. 2 for the sample of M31 globular clusters with infrared photometry. The cut is made at a projected galactocentric radius of 1.5 kpc.

sample of 23 globular clusters in M31, 16 of which have projected galactocentric radii of less than 1.1 kpc. New visual photometry is given for 15 of the nuclear globular clusters in the M31 sample. The sample of seven apparently metal-rich clusters in M31 were specifically chosen because their abundances as found from optical spectra by HBK appeared to be anomalously high for their spatial positions. The 200 in. Hale telescope points extremely well, the telescope positions were recorded in the image headers for subsequent analysis, the objects were visible in the guiding and acquisition camera, and there is no question that the correct objects were observed in all cases. There appear to be problems in certain cases with the abundances determined by HBK and with the coordinates used by HBK, and also problems with some of the previously published infrared photometry of M31 globular clusters.

Using either our own fits to the calibrating sample of galactic globular clusters for [Fe/H] as a function of $(V-K)_0$ and $(J-K)_0$ (taken from the infrared observations of ACMM) or the fits given in Brodie & Huchra (1990) and adopted by HBK, we find in Sec. 3 that the outer sample of

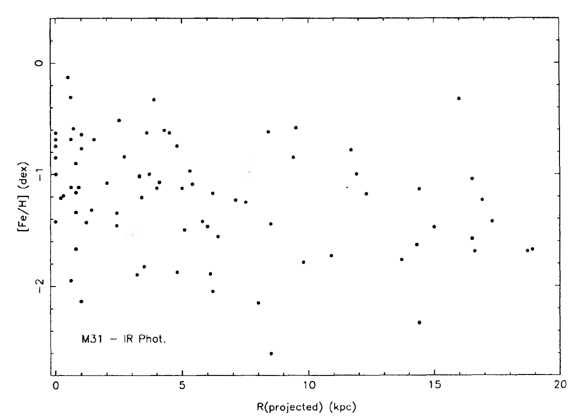

FIG. 4. Abundance as determined from IR photometry is shown as a function of projected galactocentric radius in kpc for the M31 globular cluster system.

7 globular clusters in M31 is -0.86 dex (or 1.9σ) more metal poor than was found from optical spectra by HBK. The inner sample of 16 globular clusters with IR photometry has 12 objects in common with HBK. Here the difference is smaller, only -0.22 dex, in the same sense as for the outer sample. One must always bear in mind that few of these clusters have individually determined reddenings, and we have adopted the minimum foreground reddening to M31, corresponding to $E(V-K)=0.28$ mag, and completely ignored any reddening internal to M31. This assumption is probably good for the outer sample, and poor for the nuclear sample. This assumption means that [Fe/H](IR) must be regarded as an upper limit to the actual abundance of any object.

If we combine our sample with other published photometry of globular clusters in M31, we have a total of 84 objects. Just under forty of these objects have individually measured reddenings from Searle (1980). In Sec. 4 we give a comparison of the properties of the M31 globular cluster system as viewed in the infrared with that of the Milky Way globular cluster system. We find that the two are very similar. The mean metallicity of the nuclear globular clusters in the two galaxies is the same to within 0.11 dex (29%), as is the mean metallicity of the globular clusters outside the nucleus in the two galaxies. $\Delta\{\langle[\mathrm{Fe/H}](\mathrm{M31})\rangle-\langle[\mathrm{Fe/H}](\mathrm{Milky\ Way})\rangle\}$ is within the uncertainties of the mean abundances for both the nuclear and outer samples. There is a general enhancement in metallicity in the nuclear sample in M31, which may be an artifact of reddening in the nucleus of M31, but there is no evidence among the outer globular clusters in M31 for a spatial gradient of metallicity. This too is in agreement with expectations based on what is observed in the Milky Way globular cluster system.

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